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Behavior of Historic Buildings in Zones with Moderate Seismic Activity. Case Study: Banat Region, Romania

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Abstract

Historic buildings from seismic zones have recorded important damages after earthquakes. Due to this aspect, in current design codes for consolidations of some countries there are special calculations for historic buildings. The development of the investigation methods for the damages developed in the historic bearing structures revealed the fact that these damages are differentiated by the type and intensity of the earthquake. Information on these different failure modes of the historic bearing structures is not given in the current design codes for zones with medium and reduced seismic activity. In Romania there are no specific provisions for the design of the consolidation works of historic bearing structures, even though there are two important seismic zones: Vrancea region and Banat region. The Vrancea region is characterized by deep earthquakes while the Banat region is characterized by shallow earthquakes. These two types of earthquakes produce different failure modes for similar historic buildings. In this article there are presented specific failure modes of historic buildings such as orthodox churches, catholic churches, synagogues, residential buildings, and aggregate buildings from Banat region which has moderate seismic activity. The evaluation methodology of the seismic vulnerability of buildings from historic centers developed by the University of Padova was confirmed by in situ identification of failure mechanisms recorded in historic bearing structures from Timisoara. There are also presented specific recommendations regarding the design philosophy of the consolidations for zones with moderate seismic activity, by the control of the fundamental requirements for buildings: rigidity and ductility.

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Keywords: Seismic behaviour; earthquakes; design codes; masonry structures; seismic vulnerability; historic buildings;

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1. Introduction

Historic buildings placed in seismic zones, in time have recorded important damages of their bearing structures. In order to leave future generations with valuable historic heritage assets, we are obliged to consolidate them. Today, according to the Chart of Venice, there are defined clear rules for reversible interventions on these constructions, which generate diverse procedures for the calculation of the bearing capacity of historic buildings. Past seismic recordings performed on constructions during earthquakes from 2009 until the present time, point out the fact that the bearing capacity of historic buildings must be calculated not only in function of the intensity of the earthquake, but also taking into account the earthquake characteristics. From this, several questions arise: i) how can one improve the seismic behavior of the building: controlling the ductility, strength or rigidity of the building? ii) in the attempt to consolidate a building by increasing its strength, ductility and rigidity, isn't one destroying a balance which the building had for a long time, increasing its vulnerability by changing some characteristics? iii) depending on the type of earthquake, what is necessary to control: the ductility, bearing capacity or the rigidity of historic buildings?

2. Characteristics of earthquakes from Romania

In Romania there are two important seismic zones: Vrancea and Banat. The first one is characterized by intermediate deep earthquakes at a depth of 150 km and is located at the curvature of the Carpathian Mountains. This region influences areas from the eastern and southern part of Romania and its earthquakes have long duration and a large number of cycles which create significant inelastic deformations [1]. The second seismic area is located in the western part of Romania and is characterized by shallow earthquakes, having a peak ground acceleration of 0.20g. According to Mosoarca and Gioncu [2], the earthquakes which occur in this area are characterized by: i) short periods of vibration (below 0.2 sec, up to 0.3 sec) affecting massive masonry structures; ii) pulse actions, having a powerful first cycle followed by cycles with reduced intensity; iii) important components perpendicular to the fault rupture; iv) horizontal and vertical components of the same size. The recorded intensities of the earthquakes from Banat region are presented in Table 1 [3].

Table 1. Intensities of earthquakes from Banat region on MSK scale.

Seismic intensity	V	VI	VII	VII-VIII
Year	1889	1973	1879	1879
	1896		1859	1915
	1902		1900	1991
	1907		1941	
	1950		1959	

Similarities between the seismic characteristics of Banat region can be observed in comparison with Abruzzo region from Italy, after the L'Aquila earthquake in 2009. In both cases there are shallow earth-quakes occurring at a depth between 5 km and 15 km having a large number of aftershocks after the main shock. On the Richter scale, the L'Aquila earthquake had a magnitude of 5.8, while the largest earthquake which occurred in the Banat region had a magnitude of 5.6. As in the case of the Italian earth-quake, where the vertical components of the earthquake were comparable or larger than the horizontal one (Fig. 1), large vertical components were measured also in Timisoara, the largest city from Banat region, Romania [4]. Recordings of recent earthquakes indicate peak vertical ground acceleration values as large as the

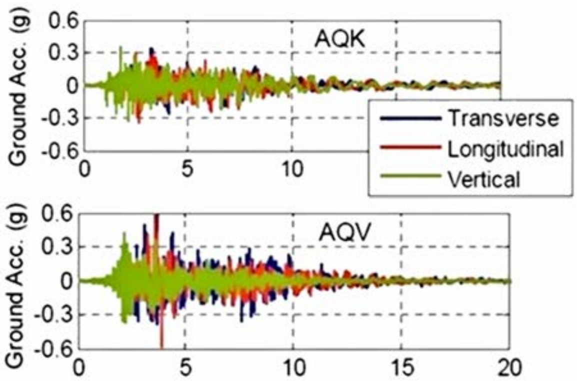

Fig. 1. Ground motion traces at near-fault stations AQK and AQV [5].

horizontal ones. The vertical forces occurring in masonry structures having vaults, cupolas and arches create tensile stresses which leads to the detachment of the masonry components.

3. Romanian seismic design codes

Technical provisions for the earthquake design of buildings from Romania has underwent a constant change, up until the present time. A first guideline was issued in 1943 regarding "Temporary instructions for preventing the deterioration of buildings due to earthquakes and restoration of the degraded ones" due to a major earthquake from 1940. The first seismic map elaborated for Romania appeared in 1952 and included the Banat region in a zone with low seismic activity (Fig. 2a), [3]. Regardless of the low seismic activity zone from Banat, the decision to include the effect of earth-quakes in the design of multistory buildings from this region was made based on some studies [6]. In 1963 modifications for the de-sign codes included the city of Timisoara from Banat region into a category of intensity 6 of the seismic activity on the MSK scale (Fig. 2b).

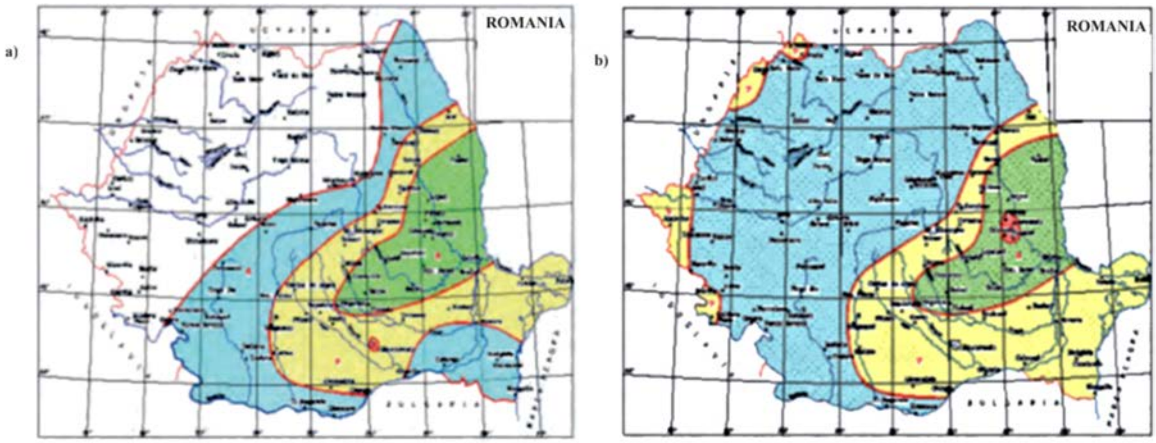

Fig. 2. Seismic zonation map – MSK scale (a) 1952, (b) 1963 [6].

These modifications were part of the design code P13-63 and the calculation of the seismic action was based on a response spectrum with the control period of 0.3 sec, characteristic for shallow earthquakes of crustal type. Following the major earthquake from Vrancea region in 1977, a common response spectrum was introduced for the entire Romania with the control period of 1.5 sec in the design codes P100-78 and P100-81 (Fig. 3a) [7]. Additional spectra were introduced in order to comply with the shallow earthquakes from Banat region having a control period of 0.3 sec and 0.4 sec. In the seismic design code P100-92 from 1992 modifications included Timisoara in a zone having the degree of intensity 7 to 7.5 on the MSK scale with a PGA 0.16g being very close to the zone of intensity 8 with PGA 0.20g (Fig. 3b) [8]. The seismic design code P100-2006 from 2006 was mainly focused on the level of PGA [9], for Banat region stating values between 0.08g to 0.20g (Fig 4a). Later modifications in 2013 changed this interval to 0.10g to 0.25g (Fig. 4b) [10].

4. Damages of historic bearing structures

An increase of the seismic intensity for the Banat region in the Romanian seismic design codes can be seen in the previous section, starting with 1943. However, following the recorded earthquakes in the Banat region from 1950, 1959, 1973 and 1991, the historic bearing structures did not record important damages and continued to develop failure mechanisms specific for this seismic zone, without any building reaching the state of collapse. As a result of this fact, several questions arise: i) why did these historic buildings not fail in time, even though the design codes constantly increased the seismic intensity of the region? ii) the given consolidation measures are based on credible values of the measurements of peak ground acceleration?

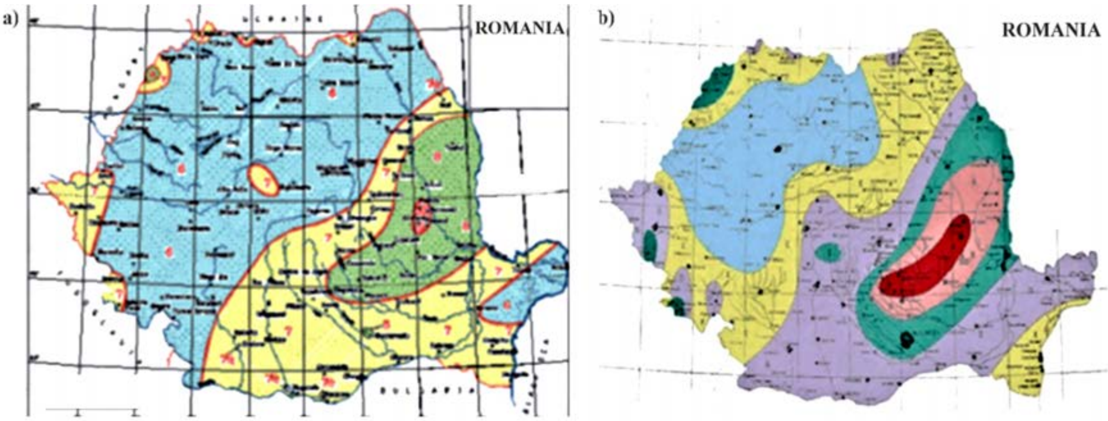

Fig. 3. Seismic zonation map – MSK scale (a) 1978, (b) 1992 [6].

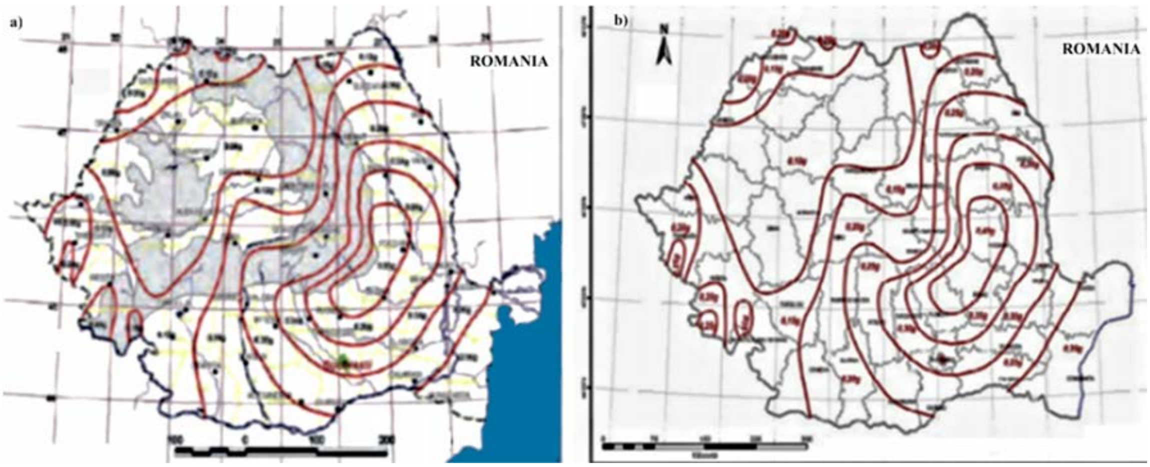

Fig. 4. Seismic zonation map – PGA (a) 2006 [9], (b) 2013 [10].

4.1. Damages of churches and synagogues

In the Banat seismic zone there are historic buildings of 3 religious denominations: orthodox, catholic and Jewish. As a result of several earthquakes, no failures of any places of worship from these denominations were recorded. The orthodox and catholic churches were built in Romanesque style. The main difference is that orthodox churches present towers and pendants, and also in some synagogues are present pendants. Generally, orthodox churches record damages in the tower and apse area. In Fig. 5 and Fig.6 there are presented these damages for a Serbian orthodox church from Birda village, Timis County, at approximately 15 km from the epicenter of the 1991 earthquake.

The church was divided into 5 rigid blocks, as it can be seen in Fig. 7, based on the damages recorded after the 1991 earthquake, having the largest damages observed in the nave and apse area. The influence of the high values of the vertical components of the seismic acceleration, characteristic for shallow earthquakes can be observed also in the arches of catholic churches and synagogues, and in large span bearing elements (larger than 10 m).

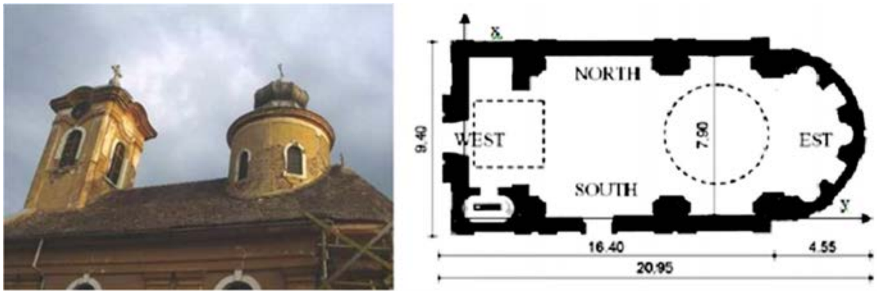

Fig. 5. View of the towers of the church and horizontal plan.

Fig. 6. Cracks in the tower, western wall and eastern wall.

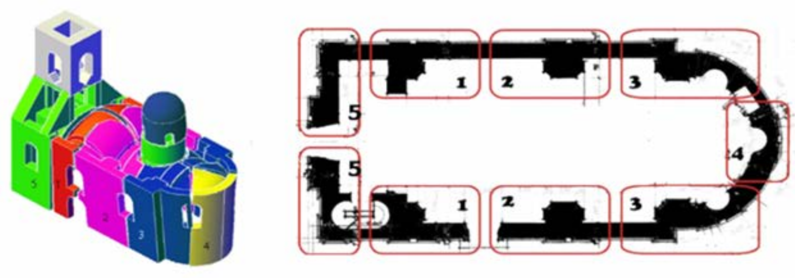

Fig. 7. Rigid blocks in the ultimate limit state and plan dimensions of the church.

In Fig. 8 and Fig. 9 there are presented cracks which appeared in the Catholic Church from Bobda village, Timis County, and in the Synagogue from the Citadel from Timisoara [11]. In order to reduce the mass and improve the seismic behavior of the cupolas, the builders renounced using brick masonry for these historic structures in favor of superb riveted steel structures.

In Fig. 10 there is presented the steel cupola from the Catholic Church from Bobda [12] village and in Fig. 11 the cupola from the synagogue from Traian Square in Timisoara. Unfortunately, lacking specific design recommendations for zones with low seismic activity, the cupola of the Synagogue from the citadel was irreversibly consolidated by casting a layer of concrete over its entire surface in the 1960's, as it can be observed in Fig. 12.

4.2. Damages to residential buildings

Historic residential buildings from Banat region are made of brick masonry with limestone mortar after the establishment of the Habsburg administration in 1716. Although buildings do not have a seismic conformation and did not use materials with high strength, there have not been recorded any earthquake failures up until the present time. Important damages have been recorded only by buildings made of unburnt clay masonry. Even though these buildings did not reach a state of collapse, according to the seismic design philosophy they represent a high seismic risk because:

- the slabs are made of timber or brick vaults, which does not ensure a rigid diaphragm;
- the bearing walls are placed on the longitudinal direction instead of the transversal one;
- the span between the bearing walls on transversal direction is larger than 6 m;
- the thickness of the walls varies on the building height, starting with 75 cm at the base and reaching 25 cm at the attic;
- unordered disposition of the compartment walls on the building height.

Fig. 8. Catholic Church from Bobda – cracks in the nave and narthex area.

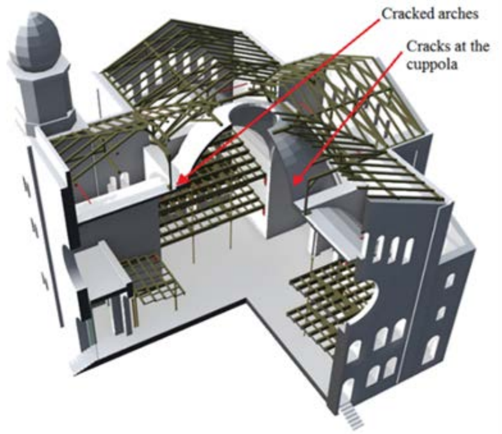

Fig. 9. Synagogue from the Citadel from Timisoara – cracks at the masonry arches and cupola.

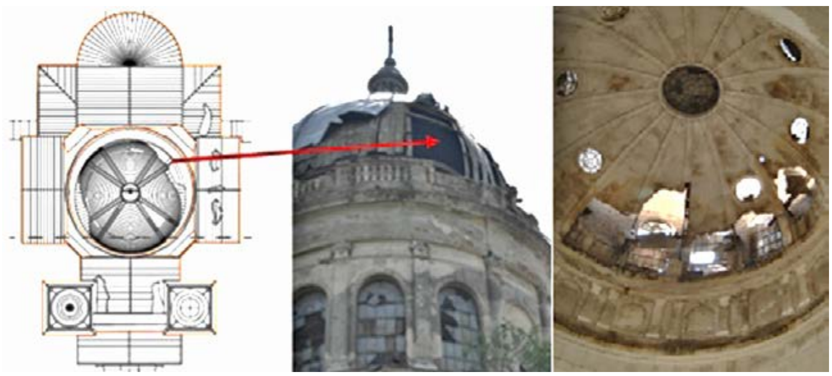

Fig. 10. Steel cupola from the Catholic Church from Bobda.

Minimum damages were recorded after earthquakes, mainly due to the removal of walls by human interventions and the aforementioned disadvantages. According to the current seismic design codes, the historic buildings from Timisoara present a high seismic risk. Recent studies were performed by researchers from Politehnica University of Timisoara in collaboration with the University of Padova for the seismic vulnerability evaluation using the Vulnus methodology [13,14]. At the same time, the study of the historical center was carried out by implementing the analysis of most relevant local mechanisms of collapse.

Fig. 11. Synagogue from Traian Square from Timisoara – steel cupola.

Fig. 12. Reinforced concrete casted over the cupola from the Synagogue from the Citadel from Timisoara.

Vulnerability maps were defined, indicating a small number of historic buildings which are vulnerable to in plane and out of plane failures [15,16], as it can be seen in Fig. 12. These results show good correspondences with the real state of these buildings in the present time.

Fig. 13. Vulnerability assessment of masonry buildings from Timisoara for (a) simple overturning failure, (b) vertical bending failure, (c) in plane failure [15-16].

Fig. 14. Steel connectors between aggregates of buildings.

Appropriate seismic behavior of historic residential buildings is due to the fact that there is a spatial collaboration between these buildings. Aggregates of historic buildings are made by the use of some steel connectors, as presented in Fig. 14, which are introduced in the construction process and by erecting common walls between buildings or providing small gaps between the walls.

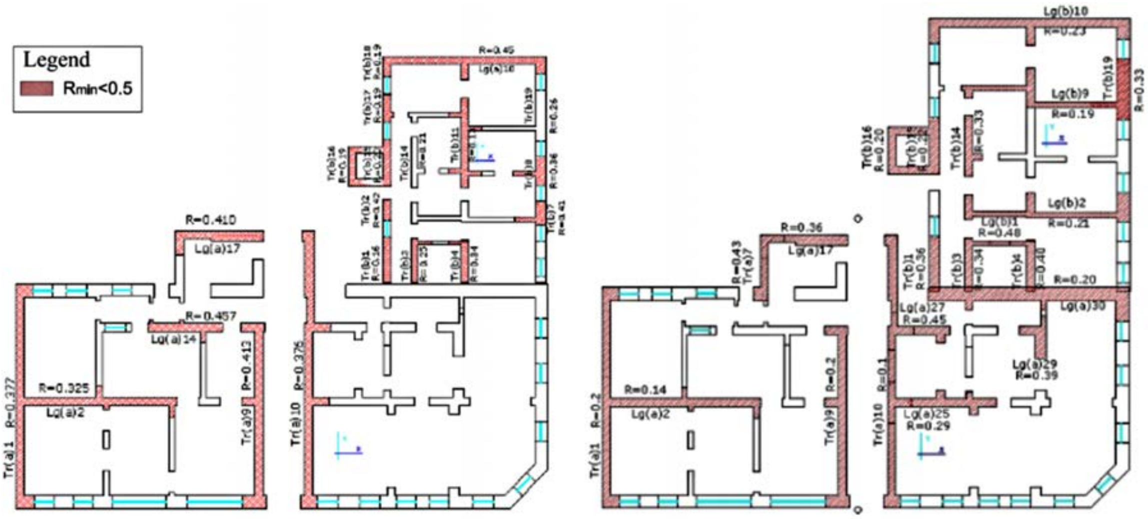

Fig. 15. Axial and shear force bearing capacity for 3 storey masonry building.

These advantages in the redistribution of seismic forces between buildings are not found in the design codes as clear recommendations for designers and experts. In Fig. 15 there are presented bearing capacity zones of a historic building having a basement and 3 stories, calculated according to the current value of the seismic force. It can be observed that approximately all the walls have their bearing capacity exceeded for axial and shear forces. However, the building constructed in 1888 did not record any important seismic damages after the expertise carried out in 2009.

The effects of increasing the rigidity of bearing structures from zones with shallow earthquakes, such as the Banat region, by using the same consolidation provisions as for entire Romania, from the point of view of the seismic forces, are presented in Fig. 16.

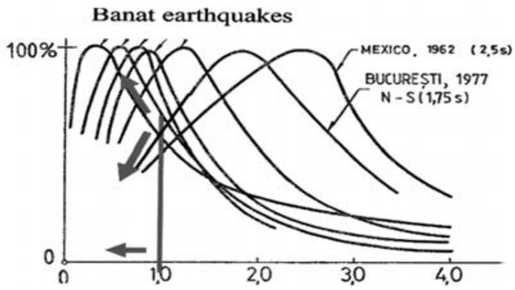

Fig. 16. Effects of increased rigidity in case of Banat region earthquakes [1].

5. Conclusions

Following the description of the different types of earthquakes from the two main seismic zones from Romania, it can be easily observed that the historic bearing structures record different failure mechanisms. However, in the current seismic design codes from Romania there are not given clear calculation and consolidation provisions for the historic structures from Banat region. Given the fact that earthquakes from Vrancea region are characterized by a long period of action with an important number of cycles, the structures will progressively develop an important number of plastic deformations, indicating the need for consolidation solutions to in-crease the ductility of these historic structures. Earthquakes from Banat region have a reduced number of cycles in a short period of time, and under seismic solicitations on horizontal direction cannot form potential plastic zones which should develop progressively. In addition to this, high speeds of the seismic waves increase the resistances of the masonry materials, making the development of potential plastic zones practically impossible. Due to this fact, providing buildings in this zone with consolidation solutions which increase their ductility is an incorrect approach. It is important to reduce the rigidity of the structure in order to reduce the value of the seismic force and to increase the resistance of the structure. From the presented facts yields that the consolidation philosophies for historic structures must be different: structures placed in seismic zones with a large number of cycles must be provided with consolidation measures which increase their ductility, while structures placed in seismic zones with shallow earthquakes must have their rigidity reduced and their bearing capacity increased with materials with reduced rigidity (steel structures, fiber reinforced polymers, etc.)

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